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Effects of Haptic Feedback in the Tele-Operation of an Unmanned Aerial Vehicle

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EFFECTS OF HAPTIC FEEDBACK IN THE TELE-OPERATION OF AN UNMANNED AERIAL VEHICLE

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This paper will describe an experiment that investigates the influence of force feedback on collision avoidance, control behavior and workload in the tele-operation of an unmanned aerial vehicle (UAV). Artificial force fields are used to provide force information. Subjects are asked to control a stability-augmented UAV helicopter through an obstacle-loaded environment. Visual information is provided by a display containing the simulated forward looking camera view and a navigation display, providing a top-down view. The force feedback algorithm is only implemented for the horizontal plane.

Problems related to the general principle of an artificial force field that occur with autonomous robots, such as difficult passage through closely-spaced obstacles or oscillatory motions of the vehicle might also occur here, and are represented by the stick motions. Various subtasks during the experiment are conducted to investigate whether these possible problems actually occur and how they affect the operator performance and workload.

The experiment results indicate that haptic feedback is very useful to assist the human tele-operator to avoid collisions, especially in cases where the visual information becomes insufficient. The minimum distance between the vehicle and an obstacle increases and the time spent within a critical distance towards an obstacle decreases, all leading to a higher level of safety.

Introduction

In the tele-operation of an unmanned aerial vehicle (UAV), the human operator is physically separated from the vehicle. This leads to the situation where the operator lacks the normally available, rich amount of information sources such as motion, tactile and auditory cues. Visual information provided by on-board cameras is dominantly used to provide the operator information about the environment. However, due to the limited camera field of view this visual information alone provides very limited situation awareness and may not be sufficient for a safe and efficient control of UAV (Diolaiti and Melchiorri, 2002, Hogan, Pollak and Falash, 2002). This can occur particularly in cases where the camera is not pointing in the direction of motion, such as in a hovering helicopter. Therefore, it is recommended to provide the operator with multi-sensory information.

Force feedback can be used to provide the operator tactile information that complements the visual information about the environment (Anderson and Spong, 1989, Elhaij, Xi, Fung, Liu, Li, Kaga and Fukuda, 2001). The integration of multi-sensory information allows an improvement of situation awareness. This paper describes an experiment, investigating the effect of haptic feedback on collision avoidance, control behavior and workload. It is structured as follows. First a brief review will be given of potential fields, mapping the environment constraints to virtual forces. Then the experiment will be described followed by the results and conclusion.

Potential Fields

In order to provide force feedback to avoid collision it is required for the control manipulator to provide the force before the vehicle actually makes contact with an obstacle (environment constraint). In literature potential fields are often used for local path planning of autonomous (ground) robots, mapping the environment constraints to the controller to avoid local obstacles (Borenstein and Koren, 1989, Khatib, 1986, Krogh, 1984). The obstacles exert virtual repulsive forces, pushing the robot away from the obstacles, whereas the goal at which the robot should arrive exerts an attractive force.

Two potential fields that are often referred in literature will be briefly discussed in this section, followed by a description of an artificial force field that was developed at this faculty.

Artificial Potentia Field

One of the first potential field was introduced by Khatib , which is called the Artificial potential field (Khatib, 1986). It depends only on the position of the system with respect to an obstacle and requires analytical description of obstacles. However, in unknown environment with complex obstacles, this field would not be suitable.

Generalized PotentialField

Krogh introduced a potential field that depends on the position as well as on the velocity towards an obstacle (Krogh, 1984), Figure 1. This type of field would be more representative for a level of danger. When the vehicle is close to an obstacle but moving away from the obstacle or parallel to an obstacle, the repulsive forces would not be large. On the other hand, when the vehicle approaches an obstacle with a large speed from a reasonable distance, the repulsive forces would be large. Additionally, the field also considers the acceleration limitation of the vehicle. However, from the application of potential fields for autonomous robots, some limitations were found. In case of closely space obstacles, the robot would move with oscillatory motions between these obstacles. A minimum in the potential field may occur, causing the robot to stop. Additionally, the generalized potential field may be too large for a reasonable velocity that may not be compatible with the operator's internal representation of the environment constraints.

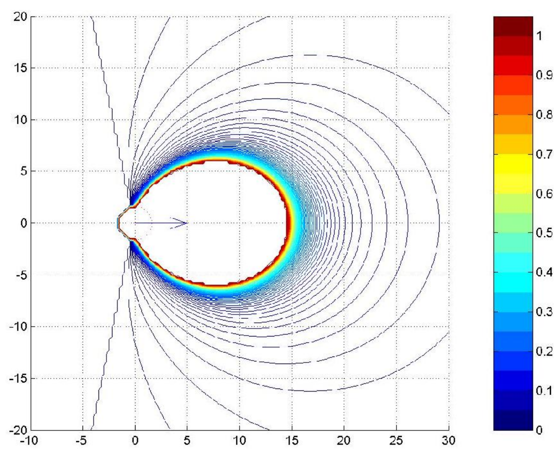


Figure 1. *Generalized potential field.*

Parametric Risk Field
Due to the challenges of the potential fields discussed above an artificial force field was developed, called Parametric risk field (Boschloo, 2004). The field is based on the principle of the generalized potential field, but it also allows the user to change its size and shape through certain parameter settings for certain tasks. Figure 2 hows a schematic presentation of the parametric risk field. Wit d_0 the width of the field can be adjusted, whereas with d_{ahead} the length of the field can be adjusted.

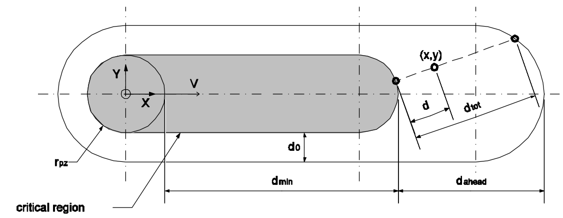


Figure 2. *Parametric risk field.*

A previous study (Boschloo, 2004) indicates that the parametric risk field can be used to avoid collision with less oscillatory motions with respect to the generalized potential field. An experiment conducted by Lam et al. (2004) showed that the parametric risk field can improve the path following performance considerably, at the cost of a higher workload.

However, the experiment involved a path following task through a tunnel-in-the-sky display of which the tunnel walls represent the environment constraints.
A more realistic experiment should be conducted having an UAV flying freely through an environment with obstacles.

Experiment

The goal of the experiment is to investigate the effect of haptic feedback on the collision avoidance, control activity and workload.

Subjects

Eight subjects with no flight experience participated in the experiment.
The main task for the subjects was to follow a trajectory without colliding with any obstacles. The trajectory contains different scenarios, in which a specific maneuver (subtask) needs to be conducted. Additionally, the scenarios are defined in such a way that they are similar to those that would introduce control difficulties for autonomous robots, found in literature.

Apparatus

The experiment was conducted in a fixed-base simulator in the Human-Machine Laboratory of the Control and Simulation division. A hydraulic driven side-stick was used to provide force feedback. Mass-spring-damper stick dynamics were simulated.

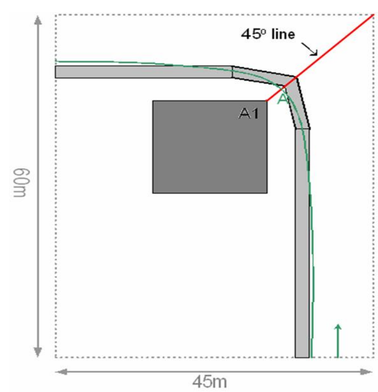
Independent Variables

There are three levels of haptic configurations (HC) and six levels of subtasks (ST). The haptic configurations are:

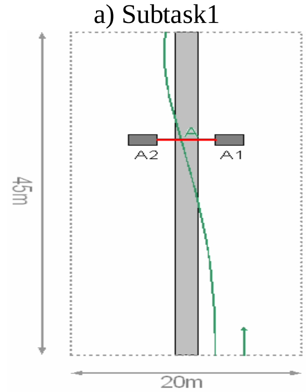
1. No haptic haptic feedback, i.e. the subjects only feel the simulated mass-spring-damper stick dynamics.
2. Basic risk field, i.e. force feedback generated by a slightly modified version of the generalized potential field.
3. Parametric risk field, i.e. force feedback generated by the recently developed force field. The parameter settings are d_0=1.5 m and d_{ahead}=2 x V, where V is the velocity.

Second, each of the subtasks will be described briefly below with the item number corresponding to the task number. The scenarios for each subtask are shown in Figures 3 and 4. In these pictures, the light gray path represents the reference trajectory, whereas the green line represents an example of a trajectory that the UAV might fly. The dark gray objects represent the obstacles.

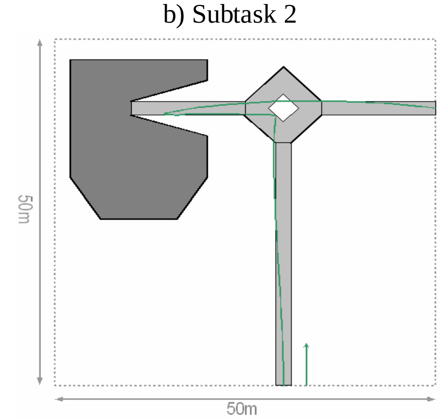
1. In this scenario the helicopter has to make a 90 degrees turn around a building. See Figure 3a. During the turn the building will be out of the camera field of view. It is expected that without haptic feedback corner-cutting effects may occur, leading to a larger amount of collisions than with haptic feedback. The length A-A1 is used to represent the minimum distance between the vehicle and obstacle.
2. In this scenario the helicopter is to fly between two closely-spaced, small obstacles. In literature, this scenario would lead to difficult or no passage with autonomous robots. It is expected that the operator needs more effort to push the helicopter through the passage, but less effort to avoid collision with either one of the obstacles. The smallest value between the lengths A-A1 and A-A2 represents the minimum distance to an obstacle. See Figure 3b.
3. This scenario demands a special task in a hovering phase of the helicopter. Once the helicopter has reached the square, it should hover backwards into the direction of A1 until the operator can see a certain stop sign fixed in the world. See Figure 3c. In this scenario, the camera visual information does not point in the direction of motion and it is expected that haptic feedback would become very useful in this kind of situations and tasks.
4. This scenario consists of a building with a discrete change in the shape of the wall. It is expected that this would lead to a discrete change in the force feedback, leading to a deviation from the reference path. See Figure 3d.
5. In this scenario two buildings with discrete changes in the opposite direction may lead to oscillatory behavior in the stick and cause considerable control difficulties. See Figure 4a.
6. In this scenario the turn radius with haptic feedback will be limited due to the obstacles in front and at the left side. It is expected that this scenario will lead to control difficulties, when approaching with high speed. See Figure 4b.



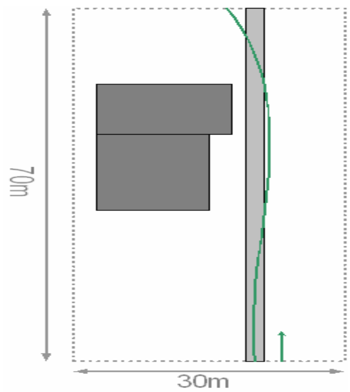
a) Subtask1



b) Subtask 2

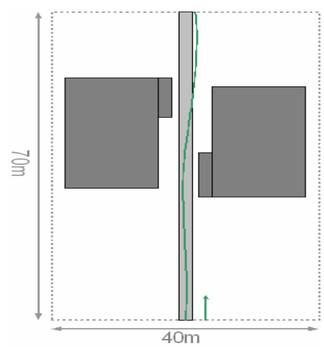


c) Subtask 3

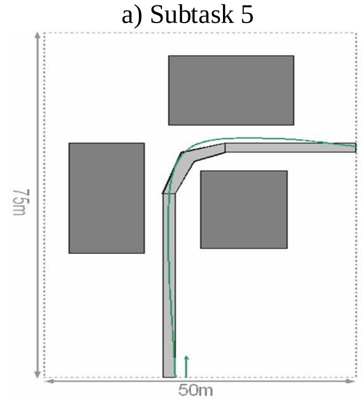


d) Subtask 4

Figure 3. *Subtasks 1 to 4.*



a) Subtask 5



b) Subtask 6

Figure 4. *Subtasks 5 and 6.*

Dependent measures

The efficiency of collision avoidance can be expressed by the number of collisions. The minimum distance with respect to an obstacle and the time spent within a critical distance to an obstacle are used as a measure for the level of safety. The standard deviation of the total exerted moment on the stick represents pilot control activity, whereas the standard deviation of the total external moment represents the haptic activity. The workload is measured by means of a TLX rating scale (Hart and Staveland, 1988).

Procedure

Each subject will fly 5 runs for each haptic configuration. Before the actual experiment, subjects get the opportunity to get familiar with the three haptic configurations by training runs. After each experiment run, subjects are asked to rate their workload using the NASA TLX rating scale.

Description of the Experiment Simulation

Display A simulated onboard camera outside visual, showing the world in a 3-dimensional fashion is projected on a large wall in front of the operator. The reference path is shown in the simulated world as a gray path on the ground, see Figure 5.

A 2-dimensional navigation display is presented on a 15 inch screen located in front of the operator between two operator seats, see Figure 6.

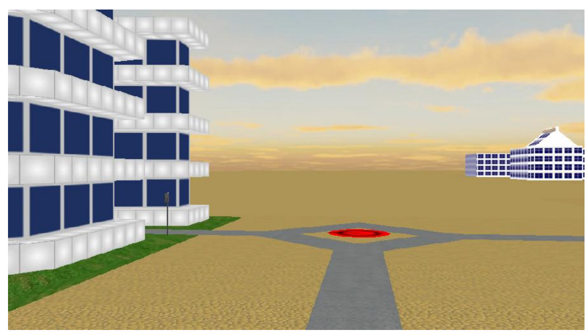


Figure 5. *Three-dimensional outside visual display.*

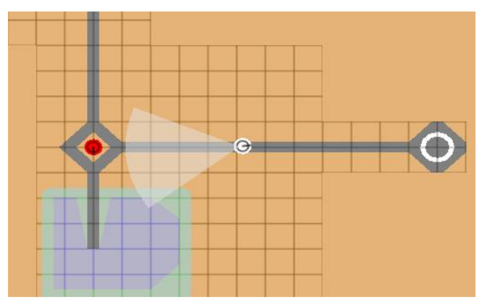


Figure 6. *Two-dimensional navigation display.*

Trajectory and helicopter model Five different trajectories are defined. Each trajectory contains three repetitions of the six scenarios in a random order. For each haptic configuration these five trajectories will be flown one time.

A stability-augmented UAV helicopter model with easy controllability is used. The model has a maximum velocity of 5 m/s and a maximum acceleration of 1 m/s^2.

Results and Discussion

The main results will be given in this section. A full-factorial ANOVA will be applied. The error bars, showing the mean and the 95% confidence intervals are shown in Figure 7.

Number of Collisions

A borderline significant effect of haptic configuration exists on the number of collisions, (HC: $F_{2,14}$=2.811, p=0.094). A Post-Hoc analysis (Student-Newman Keuls (SNK), α=0.05) reveals that in case of no feedback the most amount of collisions occur.

In subtasks 2 and 4 no collisions occur, which results in a significant effect of subtask, (ST: $F_{5,35}$=2.514, p=0.048) . Additionally, subtasks 3 and 5 lead to more collisions with no haptic feedback, resulting in a significant 2-way interaction (HC x ST: $F_{10,70}$=2.338, p=0.019).

Control Activity

A highly-significant effect of haptic feedback on the control activity was found. Independent of the subtask, the basic risk field causes the highest control activity, (HC: $F_{2,14}$=56.697, p≤0.01). A post-hoc analysis (SNK, α=0.05) revealed that the control activity is lowest with no haptic feedback and highest with the basic risk field.

Also a highly-significant effect of subtask was found, resulting in a high control activity in task 3 and low activity in tasks 2 and 4 with no haptic feedback and parametric risk field, (ST: $F_{5,35}$=16.966, p≤0.01). In subtask 3 the stick deflections are equivalent for the haptic configurations, in contrast with other subtasks. This expresses the highly-significant interaction, (HC x ST: $F_{10,70}$=22.564, p≤0.01).

Haptic Activity

The haptic configuration has a highly-significant effect on the haptic activity, (HC: $F_{2,14}$=211.024, p≤0.01). A post-hoc analysis (SNK α=0.05) showed that the basic risk field causes the highest haptic activity.

However, subtask 3 does not lead to a high haptic activity, causing a highly-significant effect of subtask, (ST: $F_{5,35}$=35.5, p≤0.01).

As can be seen in Figure 5b, subtasks 5 and 6 lead to higher haptic activity from the parametric risk field with respect to other subtasks, whereas it is not the case for the paremetric risk field. This causes a highly-significant interaction, (HC x ST: $F_{10,70}$=50.697, p≤0.01).

Minimum Distance from Obstacle

A highly-significant effect of the haptic configuration on the minimum distance from an obstacle exists, (HC: $F_{2,14}$=19.221, p≤0.01). A post-hoc analysis (SNK α=0.05) revealed that the basic risk field yields the largest distance, whereas no haptic feedback leads to the smallest distance to an obstacle.

In subtasks 2, 3 and 5 small distances occur with respect to other tasks. This expresses the highly-significant effect of subtasks, (ST: $F_{5,35}$=48.084, p≤0.01). For subtasks 2 and 3, the basic field does not yield the largest distance, expressing the highly-significant interaction, (HC x ST: $F_{10,70}$=17.488, p≤0.01).

Time Within Critical Distance

Only for subtasks 3, 5 and 6 the time can be measured, during which the helicopter is in a distance of 0.5 m or less from the obstacle.

A highly-significant effect of haptic feedback and subtask exist on the time, (HC: $F_{2,14}$=17.149, p≤0.01; ST: $F_{2.14}$=12.499, p≤0.01). For subtask 6 the difference between the haptic configuration, which expresses the significant interaction, (HC x ST: $F_{4,28}$ = 3.785, p=0.014).

Workload

Since the TLX is rated for a whole run, containing all subtasks, the workload cannot be distinguished for the different subtasks.

A highly-significant effect of haptic configuration leads to a highest workload by the basic risk field and the lowest workload in case of no haptic feedback, ($F_{2.14}$=39.717, p≤0.01).

From the six weightings, the physical demand, the effort and the frustration level play the greatest part in the high workload introduced by the haptic feedback.

Discussion

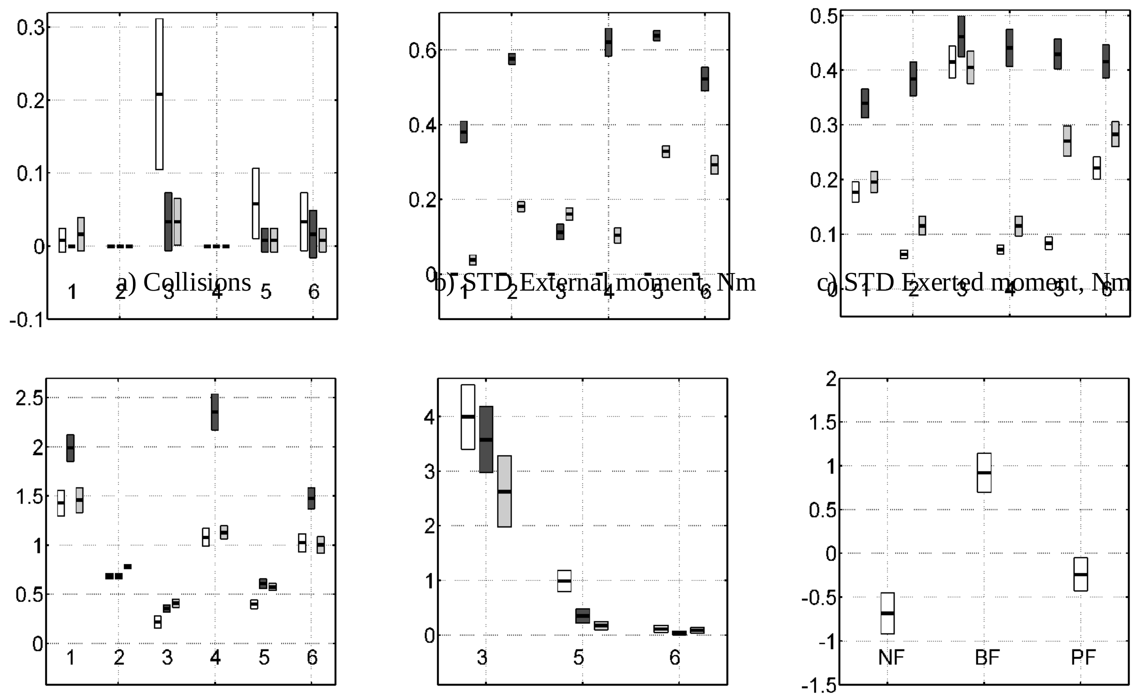
For simple subtasks such as in scenarios 2 and 4 no collisions occurred, independent of the haptic configuration. For scenarios 1 and 3, where the visual information becomes insufficient, the amount of collision can be reduced with haptic feedback. For complex subtasks in closely-spaced obstacles such as in scenarios 5 and 6 haptic feedback can even reduce the amount of collisions considerably.

Conclusions and Recommendations

Haptic feedback can assist the tele-operator to avoid collisions in complex tasks, where visual information becomes insufficient. Also the distance from the obstacle and the time spent within a critical distance are improved with haptic feedback, contributing to a higher level of safety. However, the reduction of collision and the improvement of the level of safety are at the cost of a higher workload and control activity.

Although it is shown that haptic feedback can improve the collision avoidance, it is unclear whether it can be related to an improvement of situation awareness. Therefore, it is recommended to employ a situation awareness assessment.

Information transportation time delay may well affect the collision avoidance performance and stability of the human-vehicle system. Time delay should be included in the system and investigated as well, in particular the effects on the biophysical feedback in narrow corridors.



a) Collisions b) STD External moment, Nm c) STD Exerted moment, Nm

d) Minimum distance, m e) Time within critical distance, s f) Workload, TLX z-score

Figure 7. *The mean and 95% confidence limits. The numbers 1 to 6 represents the subtasks. The white, dark gray and light gray bars represent the no haptic feedback (NF), basic risk field (BF) and parametric risk field (PF), respectively. Note that in f) the error bars are categorized by haptic configuration.*

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